CTS: Frequency Response as a Function of Temperature

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Abstract. This is an investigation report concerning the use of ground-based thermal vacuum test results to calibrate IF frequency as a function of SAW temperature, and also channel number.

1. Introduction

The MIRO instrument utilizes a Chirp Transform Spectrometer (CTS) to provide a very high spectral resolution capability for the submillimeter band. The CTS provides 4096 channels, each approximately 44 kHz wide, for a total bandwidth of 180 MHz. The input bandwidth and center frequency are 178 MHz and 1350 MHz respectively. The Surface Acoustic Wave (SAW) devices used in the CTS are constructed of $LiNiO_3$. The SAW devices are temperature controlled at discrete setpoints from 0 to 70° C in increments of 10.

The input frequencies to the CTS are preprocessed by an analog Intermediate Frequency processor (IFP) that accepts certain frequencies in the 6-16 GHz range and mixes them down to the 1350 MHz center frequency range of the CTS. IFP frequency translation is described in Table 1. Frequency stability in the IFP is provided by an ultra-stable oscillator (USO).

This technical note addresses the susceptibility of the CTS frequency response to changes in temperature. During the course of the MIRO instrument testing program, we placed the entire MIRO instrument inside a thermal vacuum (TV) chamber at JPL and performed a variety of tests. One of these tests was to insert a set of fixed narrow-band frequency signals into the input of the IFP and measure the response of the CTS. These tests were performed with the SAW filters stabilized at different thermal regimes chosen to sample the range of temperatures expected in flight.

In the following analysis an expression is derived for converting a measured channel number and SAW temperature into a calibrated frequency, along with a procedure that is needed for shifting spectra taken at different temperatures so that they can be coadded and calibrated.

2. Test Configuration and Data

The entire MIRO flight instrument was placed inside a Thermal Vacuum (TV) chamber at JPL and tested prior to delivery to ESA. In May and June, 2001, tests were carried out to determine the temperature susceptibility of the CTS. For these tests a broadband signal coupler was inserted into the first IF ahead of the IFP as shown in Fig 1 below. The signal generator was outside the thermal vacuum chamber; its output signal was passed through a vacuum isolation port. The frequency uncertainty of the signal generator was estimated to be less than 1.5 Khz. The SAW devices were temperature controlled by the MIRO instrument control software. These

Table 1. LO Mapping for IFP
LO 1 : 140703.25 4xLO 1 = 562813 LO 2 : 2182 LO3 : 7147 LO4 : 7728
Spectrometer Bandwidth: 1260 - 1440 MHz

Lines	RF (MHz)	IF 1 smm mixer 4xLO1	IF 2 M1 2xLO2	IF 3 M2 LO4	IF 4 M3 L04	IF 5 M4 LO4	IF 6 M5 LO3	IF 7 M6 LO2	IF 8 M7 LO3	IF 9 M8 2xLO2	IF 10 M9 LO4	Output to cts
$H_2{}^{18}O$	547677	15136	...	...	...	...	7989	5807	1340	...	...	1340
$H_2{}^{17}O$	552022	10791	6427	...	...	1301	...	...	...	...	...	1301
CH_3OH	553146	9667	14031	6303	1425	...	...	...	...	...	...	1425
$H_2{}^{16}O$	556936	5877	...	...	...	...	1270	...	...	...	...	1270
CH_3OH	568566	5753	1389	...	...	...	...	...	...	...	...	1389
NH_3	572498	9685	14049	6321	1407	...	...	...	...	...	...	1407
CO	576268	13455	9091	1363	...	...	...	...	...	...	...	1363
CH_3OH	579151	16338	...	...	...	...	9191	...	2044	6408	1320	1320

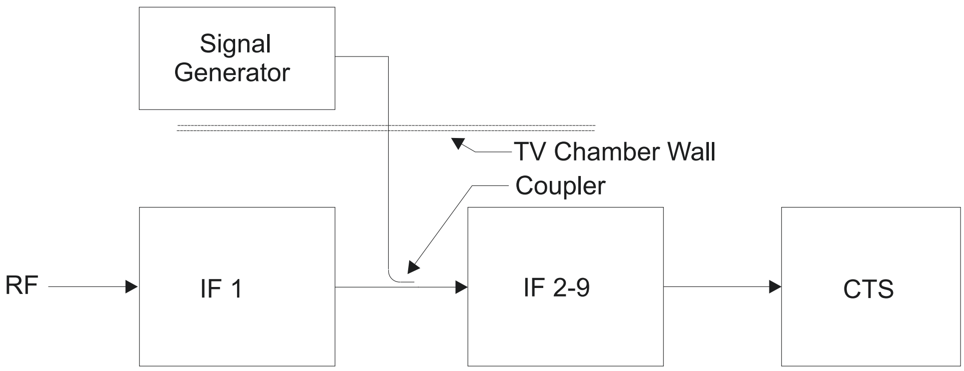

Figure 1. Test Configuration for CTS Frequency Response.

were measured using the permanently installed temperature sensors on the SAW devices. They are estimated to be sensitive at a digital quantization level of about 34 mK.

Tests were performed by setting the SAW devices in the CTS to a specified temperature and then inserting a series of 8 different frequencies (5.753, 5.877, 9.667, 9.685, 10.791, 13.455, 15.137, 16.338 Ghz) into the signal coupler. The IFP translated these signal generator tones into intermediate frequencies (1389, 1270, 14.25, 1407, 1301, 1363, 1339, 1320 MHz) at the input to the CTS. After cycling through the 8 frequencies, the SAW temperature was changed and the frequencies were recycled. At each temperature and frequency setting, the bin number of the signal was recorded. Table 2 gives the measured channel number for each frequency and temperature setting.

At any given temperature, the test data can be represented approximately by a linear equation of the form of eq (1), below, where the slope is a temperature dependent bin width, along with an offset, which is also temperature dependent. The approximate linearity of the CTS at a given frequency can be seen by plotting the input frequency as a function of the channel number. Figure 2. shows these data for the minimum ($9.6°C$) and maximum temperature ($68.2°C$) settings. A systematic offset, as well as a discernible change in slope, can be seen with these two curves. This is the temperature dependence under consideration.

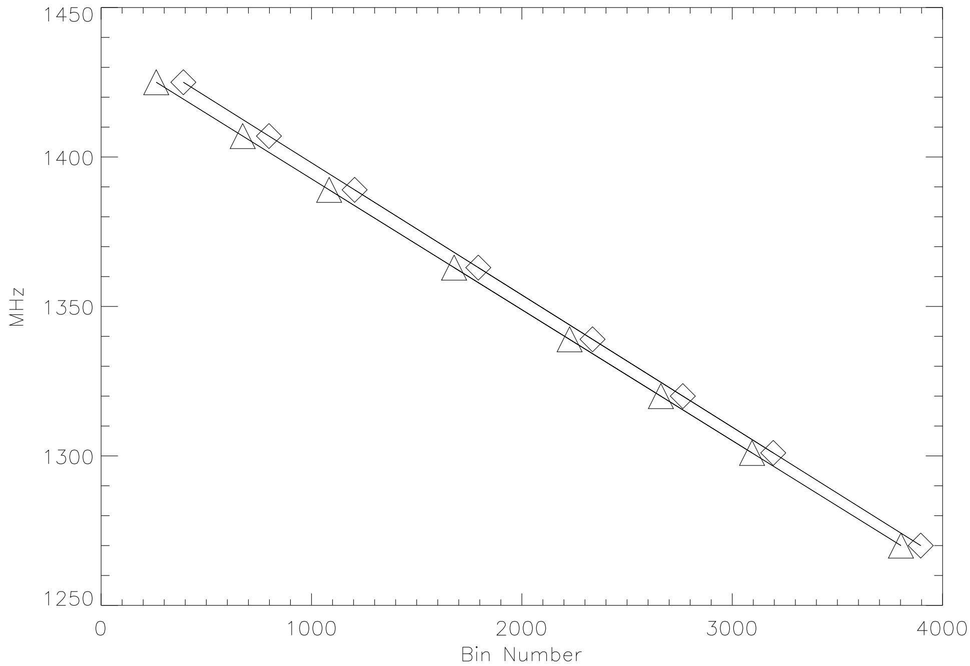

Figure 2. Frequency vs Bin Number. The diamonds are data taken at $9°C$, and the triangles are data at $68°C$.

3. The Model Function

The assumption that the spectral bin width is linearly dependent upon temperature leads directly to an expression linear in temperature, spectral position, along with a cross term. Let

F:	IFP Frequency (MHz)
T:	SAW temperature (°C)
N:	Bin (or channel) number (0-4095)

where N is the bin number showing the response to the input frequency, F. Consider a model

$$F = \alpha(T)N + \beta(T) \tag{1}$$

where $\alpha = \alpha_0 + \frac{\partial \alpha}{\partial T}_{|T_0}(T - T_0)$ and $\beta = \beta_0 + \frac{\partial \beta}{\partial T}_{|T_0}(T - T_0)$ give the bin width and intercept as first order Taylor expansions around some arbitrary center temperature T_0. Substituting these expressions for α and β into eq (1) results in

$$F = \frac{\partial \beta}{\partial T}_{|T_0}(T - T_0) + \alpha_0 N + \frac{\partial \alpha}{\partial T}_{|T_0} N(T - T_0) + \beta_0. \tag{2}$$

If it is assumed that α and β are indeed linear functions of T then the partials become constants, and the products of the partials with T_0 can be ignored since we are free to choose T_0 to be

Table 2. Bin Numbers in Response to Injected Frequencies

IFP GHz:		5.753	5.877	9.667	9.685	10.791	13.455	15.137	16.338
CTS MHz:		1389	1270	1425	1407	1301	1363	1339	1320
2001 DOY	$T\ ^\circ C$[a]								
158 19:37	68.2	1084	3802	262	673	3094	1678	2227	2661
154 13:55	58.5	1104	3818	284	694	3111	1697	2245	2678
158 22:10	58.4	1104	3818	284	694	3111	1698	2245	2678
159 09:07	48.7	1125	3834	305	715	3128	1717	2263	2696
154 23:04	39.4	1140[b]	3846[b]	324[b]	735[b]	3144[b]	1736	2281	2713
159 12:02	38.9	1145	3849	327	736	3145	1736	2281	2713
155 03:23	29.3	1161[b]	3863[b]	347[b]	757	3161	1755		
159 18:19	19.37	1185	3880	370	778	3178	1774	2318	2748
159 21:12	9.6	1205	3896	391	798	3195	1793	2336	2765

[a]One of the four SAW temperature sensors, spect_t1.
[b]Omitted from fit, poor CTS thermal controller stability.

zero. To simplify notation set $a = \dfrac{\partial\beta}{\partial T}$, $b = \alpha_0$, $c = \dfrac{\partial\alpha}{\partial T}$, and $d = \beta_0$. A predicted F is then written as

$$F = aT + bN + cNT + d, \tag{3}$$

which provides a model in which F is expressed as a linear function of the parameters to be fitted, a, b, c, and d.[1]

4. Physical Motivation of the Model

The development of a theoretical argument to justify eq (3) is a work in progress. If we assume that the sound velocity of the propagating medium in the SAW is linearly dependent upon temperature, then the constant sampling and integration times at the output will be multiplying segments of the chirp of varying width, leading to the conjectured change in channel width, α, as a function of temperature. An alternative view of the situation is that the distance traversed by the chirp in the medium varies with temperature as the SAW thermally dilates or contracts. In either case the timing of the arrival of the chirp at the SAW output is thermally modulated. Similar arguments can be made for the intercept term, β.

5. Results of the Regression

Table 2 tabulates the test data from the thermal vacuum testing at JPL in the Summer of 2001. The CTS thermal control was set above the ambient temperature in each thermal regime. The SAW temperature for each test[2] is shown in the temperature column of Table 2. The estimated parameters for the fit are shown in Table 3, along with their standard errors. The residuals

[1]The linearity assumption was tested using eq (2) as the model, where the partials, α_0, and the constant, β_0, were estimated linearly for various trial values of T_0. It was found that changes in the estimates as T_0 was varied were insignificant.

[2]Thermal stability at the various setpoints is important. By re-examining the acquired data corresponding to outlier residuals, many tests were found to have been run during unstable regimes.

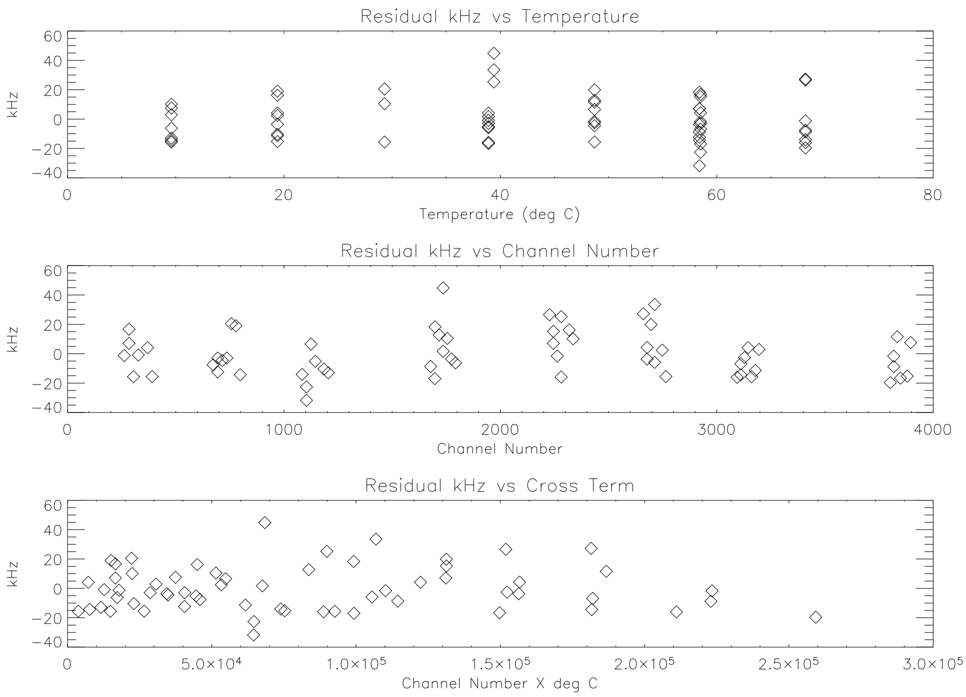

Figure 3. Residuals plotted against temperature, channel number, and cross term.

are plotted in Figure 3, and can be seen generally to be within one bin width, nominally about 44KHz. Measurements that were excluded from the fit owing to lack of thermal stability are marked. Because the residuals are small, within the precision limited by the bin width, and because they exhibit no noticeable patterns, we conclude that higher order terms in the Taylor expansions used in eq (2) are not required.

Table 3. Fitted Model Parameters

	Units	Value	Std error
a	MHz per deg C	-0.0996154	0.0002
b	MHz per Channel	-0.0443027	0.0000042
c	MHz per [chnl*deg C]	7.66259×10^{-6}	8.9×10^{-8}
d	MHz	1443.27	

6. Independent Model Verification using an Anomalous Birdie

The CTS exhibits an intermittent, weak, but sharp, spike feature, whose conjectured origin in the IFP circuitry is under investigation. An example is plotted in Figure 4. The conditions for its appearance or disappearance are not yet known. The feature does not appear in the differenced spectra, one indication that it originates in the IFP, downstream from the first mixing stage, where a 10MHz frequency shift occurs. Remarkable constancy is demonstrated using the thermal correction parameter estimates to predict the CTS frequency needed to

Table 4. Selected IFP Birdie Appearances

2001 DOY	SAW $T\ ^\circ C$	Bin Number	Predicted Input MHz
153 21:05	48.69	1694	1364.00
154 04:44	54.06	1682	1364.06
154 07:38	52.9	1686	1363.99
154 13:54	58.47	1674	1364.03
154 18:56	48.71	1694	1364.00
154 23:09	39.6	1711	1364.04
155 04:06	29.2	1732	1364.02
156 02:30	68.2	1655	1364.02
158 22:10	58.4	1675	1363.99
159 09:07	48.6	1694	1364.01
159 15:08	29.14	1732	1364.02
159 18:19	19.4	1752	1363.98
159 21:12	9.54	1771	1363.99

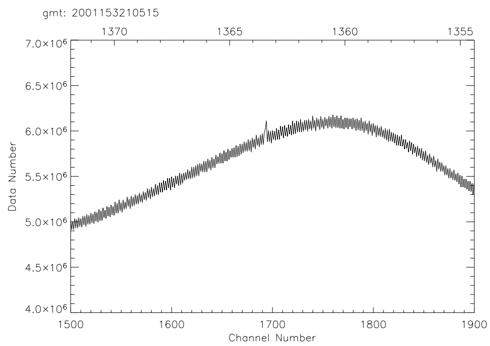

Figure 4. Example of the IFP birdie.

produce the responses shown in Table 4, where the calculated frequencies are listed in the righthand column. The average value is 1364.01 $\pm$ 0.007 MHz. With reference to the LO mapping shown in Table 1, it is indicated that the signal originates somewhere along the path for 13456 MHz, in the penultimate row of the table.

7. Frequency Corrections for Calculating with Spectra

To perform calculations with spectra acquired at different CTS SAW temperatures, it is necessary to calculate with power levels from the same frequency instead of the same bin number. It is therefore required to rebin a set of spectra to reflect what would have been acquired at a standard operating temperature. For T_0 as the standard temperature, data taken at T_1 can be rewritten as a T_0 spectrum using

$$N_0 = \frac{a(T_1 - T_0) + bN_1 + cT_1N_1}{cT_0 + b}, \tag{4}$$

where N_1 runs over all the bins from 0 to 4095. Eq (4) is derived from eq (3) by equating the input frequencies giving (N_1, T_1) to those for a set of (N_0, T_0), in other words by writing

$$aT_0 + bN_0 + cT_0N_0 + d = aT_1 + bN_1 + cT_1N_1 + d \tag{5}$$

and solving for N_0. The value from each N_1 is placed at the corresponding N_0 of the temperature standardized spectrum. The quantization error introduced could be mitigated by refining this type of calculation with a suitable linear interpolation, using the same techniques employed to adjust spectra for Doppler shifts.

8. CTS Pulse Position

The CTS digital logic accepts a command to determine the timing of the pulse to be converted to a chirp. This affects the bin number corresponding to a given test frequency. The nominal flight value for this parameter is 410, which is the value at which all of the frequency response testing in this analysis was run. During ground testing and also as part of the standard in flight payload checkout procedure, the effect of this parameter was tested. The effect is measured by a shift in the bin number of the birdie discussed above.

Table 5. Bin Numbers of Birdie at Test CTS Pulse Positions

Year/ DOY	T °C[a]	Pulse Position	Birdie Bin	Bin No. @ 68°C	Bins per Pulse Pos.
2001 164 1103	45.95[b]	412[c]	1698	1654.4	
2001 164 1113	44.07	510	2102	2056	4.10
2001 164 1122	42.53	310	1305	1253	4.02
2001 164 1128	41.34	410	1707	1654.3	4.02
2004 091 0258	23.88	410	1743	1656.2	
2004 091 0304	24.20	510	2142	2059.0	4.03
2004 091 0314	25.01	410	1740	1655.4	4.04
2005 088 0656	67.84[d]	410	1654	1654	
2005 088 0704	67.94	510	2054	2054	4.00
2005 088 0730	67.94	410	1654	1654	4.00
2005 276 1353	67.90	410	1654	1654	
2005 276 1358	67.90	510	2054	2054	4.00
2005 276 1411	67.90	410	1654	1654	4.00

[a]One of the four SAW temperature sensors, spect_t1.
[b]Thermal vacuum testing. Not thermally stable.
[c]Questionable, from test log entry, probably 410.
[d]Only this later flight data was thermally stable.

Table 5 shows results from pulse position testing to date. Using the technique described in the preceding section, the birdie position is transformed to a standard temperature, in this case 68°C. The rate of change in bin numbers per single digit of pulse position parameter setting is shown in the right hand column. Because the CTS SAW filter was thermally stable for testing after 2005, it is believed that 4.0 bins per parameter unit is the best estimate.

This rate may well be independent of SAW temperature, but subsequent tests with adequate thermal stability will be required to verify that. Figure 5 portrays the situation in

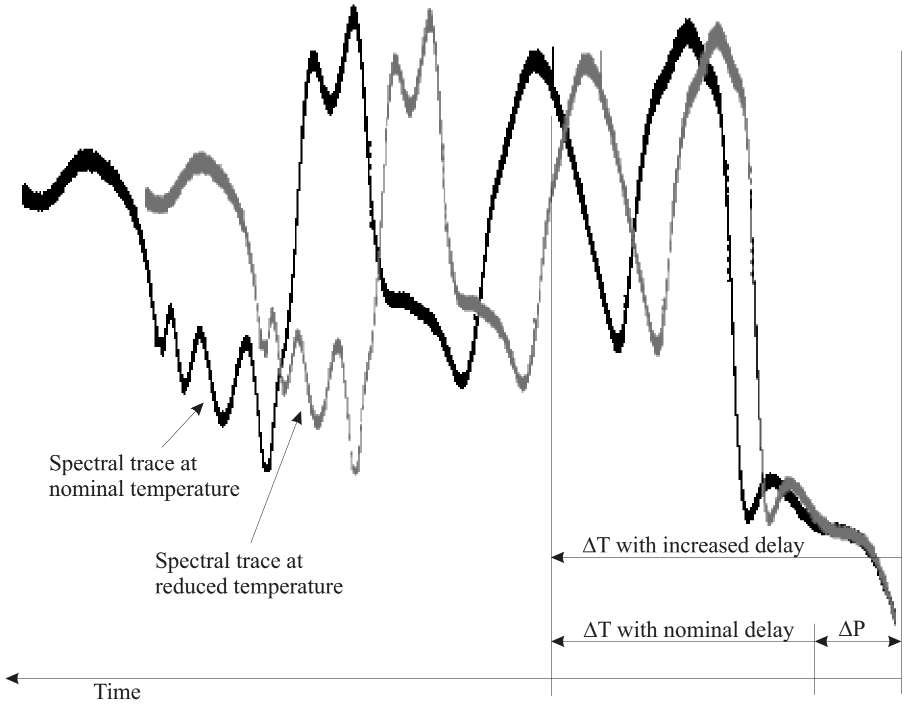

Figure 5. Plot showing relative effects of changes in temperature and pulse position.

schematic form, where the spectra are shown oriented with frequency increasing from left to right, and bin number going the opposite way, with time. The spectrum emerges from the CTS as a time series which is sequentially digitized at fixed sampling intervals. Changing the pulse position parameter changes a delay, by ΔP, from the CTS cycle start time for the pulse transmitted to the SAW to create the chirp. Increasing that delay advances the bin number at which a given fixed spectral feature, in this case the birdie, is seen. Temperature change, on the other hand, has a different effect, in which the spectrum is dilated or contracted with respect to time, and consequently with respect to bin number.

In the highly unlikely event that the CTS needs to be run at a different pulse position, the procedure for frequency calibration would involve an initial step to adjust the measured bin number to the number that would have been seen using the nominal value of 410,

$$B' = B - 4(P - 410), \tag{6}$$

where P is the new pulse position parameter value. After that the corresponding frequency would again be calculated with eq (3).

9. Concluding Remarks

We have shown that a simple linear model accounts for enough variation in frequency response to restrict the great majority of the residuals to a band comparable to the measurement sensitivity, the bin width, of the CTS, namely to a range within 44 kHz. With more sophisticated physics in support of a ramified model it might be possible to use our test data to measure a second order temperature effect. Because we would be moving within our levels of measurement quantization error, more demanding statistical analysis would be required, in which the variances implied by the quantization errors, 1/12 of the measurement intervals[3], would be added as weights to the regression problem.

Furthermore, in our measurement situation the independent variables were in fact SAW temperature and injected IF frequency, with the the peak bin number as the response or dependent variable. For a truly rigorous statistical analysis the model should be written that way, in order to make significance tests meaningful. The desired results, calibrated frequency as a function of T and B, and a rebinning procedure, could then be constructed by solving the model equation, with its marginally more rigorously estimated parameters, for F.

[3]This also applies to the digitzed SAW temperature sensor data.